AFRL-OSR-VA-TR-2014-0128

INTEGRATED THEORETICAL, COMPUTATIONAL, AND EXPERIMENTAL STUDIES FOR TRANSITION ESTIMATION and CONTROL

TEXAS ENGINEERING EXPERIMENT STATION COLLEGE STATION

William S. Saric

06/03/2014

Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTE
Arlington, Virginia 22203
Air Force Materiel Command

FINAL REPORT

William S. Saric

To: RENGASAMY PONNAPPAN
Email: Rengasamy.Ponnappan@afosr.af.mil

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Subject: FINAL TECHNICAL REPORT SPONSOR:

AFOSR/NASA National Science Center for Research in Hypersonic Laminar-Turbulent Transition

Integrated Theoretical, Computational, and Experimental Studies for Transition Estimation and Control

GRANT NO. FA9550-09-1-0341

PERFORMANCE PERIOD: 01 APRIL 2009 – 30 NOVEMBER 2013

Previous Program Manager: John Schmisseur john.schmisseur@afosr.af.mil

Principal Investigators:
William Saric saric@tamu.edu
Rodney D. Bowersox bowersox@tamu.edu
Helen Reed Helen.reed@tamu.edu
Sharath Girimaji girimaji@tamu.edu
Edward White ebw@tamu.edu
Simon North swnorth@tamu.edu
Hermann Fasel faselh@mail.arizona.edu
Joseph Shepherd joseph.e.shepherd@caltech.edu
Anatoli Tumin tumin@email.arizona.edu
Xiaolin Zhong xiaolin@seas.ucla.edu
Hans Hornung hans@galcit.caltech.edu

Consultants
Eli Reshotko exr3@case.edu
Alexander Fedorov afedorov55@gmail.com

The executive summary encapsulates the work of the *AFOSR/NASA National Science Center for Research in Hypersonic Laminar-Turbulent Transition* hereafter referred to as NHSC. It includes a brief description of accomplishments in the order: (1) Executive Summary; (2) Experimental Facilities and Results; (3) Theoretical and Computational Modeling; (4) Students and Publications. This is followed by ten volumes of details contained in dissertations.

1. EXECUTIVE SUMMARY

1.1 Overview

The NHSC was originally established for 5 years beginning 1 April 2009 at a funding level of $2 million per year with AFOSR paying the first half and NASA paying the second half. Dr. William Saric was the Center Director. Due to sequestration in the spring of 2013, NASA was unable to honor its last increment of funding so that it was effectively a four and one-half year program. Since the Texas A&M Board of Regents approved the "Center", it was decided to keep this designation for future funding and to have Drs. Rodney Bowersox and Helen Reed as co-Directors.

The NHSC was made up of 11 Professors and 2 consultants. The participating universities were California Institute of Technology (Caltech), Texas A&M University (TAMU), University of California – Los Angeles (UCLA) and University of Arizona (UA). TAMU was the lead and subcontracted to the other universities and consultants. The participants were chosen from the leaders of the high-speed transition community who covered all of the relevant areas of analysis, computation, experiment, facilities, and diagnostics. The group had one dedicated Technical Exchange Meeting (TEM) each year whose venue rotated over the four universities. They also conducted mini-TEMs twice a year at the two relevant AIAA meetings (Jan/June). These were open to the public.

In this summary, the format [**] is used to reference the relevant publication that was produced as part of the center. Following the Executive Summary, the detailed reports from each co-PI are contained in individual volumes.

1.2 Highlights

1.2.1 Three major hypersonic facilities made operational at TAMU and a fourth, T5 at Caltech, was improved so that it was able to measure Mack modes.

1.2.2 Three new diagnostic tools developed (FST, FLDI, VENOM).

1.2.3 Nonlinearities measured with FST. Then, Klebanoff-type streaks were observed with IR Thermography. This complements the computational predictions of Fasel (3.4) and Reed (3.1).

1.2.4 First measured transient growth streaks in a hypersonic boundary layer.

1.2.5 Developed in-house LST/PSE/NPSE with V&V for comparisons with experiments and with DNS (nonlinear breakdown).

1.2.6 Explained the pressure-based mechanisms that lead to stabilization in hypersonic flows.

1.2.7 Showed that pressure-field evolution exhibits a three-stage transition process which was also shown in the DNS.

1.2.8 Clarified the terminology for the second-mode.

1.2.9 Demonstrated that discrete-mode branching can be resolved with PSE.

1.2.10 The second-mode stabilization with porous coatings has been put on firm ground with the combination of theory, DNS, and experiment done by Fedorov, Hornung, Fasel, and Zhong as part of the NHSC.

1.2.11 As another example of multiple PIs interacting across the center, useful models for including chemistry have been advanced by Tumin, Girimaji, Fasel, Reed, and Zhong as part of the NHSC.

1.2.12 The spatial DNS calculations showed that nonlinear wave interactions (Klebanoff-type breakdown with streaks), the Gaster wave packet, and the turbulent spot all had remarkable similarities to what was observed in incompressible boundary layers. Thus, it appears that we already can classify the fundamental mechanisms for breakdown in hypersonic boundary layers and we need to concentrate on the details.

1.2.13 41 PhD students were supported by NHSC. 47 journal articles and 130 conference proceedings were written by NHSC.

1.3 Recommendations

The Orr-Sommerfeld Equation (OSE) is 111 years old and progress in boundary-layer stability and transition has been slow – much of it occurring over the past 50 years. A review of the history shows that major breakthroughs have been made on a scale of 10 years. This doesn't mean that once every ten years someone has a good idea. Rather, given an area of stability/transition research such as receptivity, nonlinear interactions, 3-D boundary layers, transient growth, etc., it takes ten years of continuous hard work on a transition problem in order to make a meaningful contribution.

The team structure of the Center really came together after the infrastructure was established. Productivity and cooperation increased each year and important results were being generated. This was a worthwhile activity for everyone associated with the Center. If transition continues to be an important issue for the Air Force, a successful working model has been established. It took a heroic effort to support the multiple PI NHSC and it was difficult to sustain the funding. Perhaps small computational/experimental teams can be supported out of the core program.

Before things get too far along, we should like to suggest an AFOSR/NASA-sponsored international workshop on hypersonic transition that can build on the very successful NHSC supported workshop held in Sedona 2012. The NHSC can then review all of their accomplishments for the entire community. It was thought that the NCTAM held this year would do this but the conflict with the AIAA summer meeting prevented this from happening.

New ideas are necessary. Approaching receptivity and stability as an initial-value problem is the only way to get away from eigenvalue calculations. Solutions of OSE only provide correlations. The federal agencies must be willing to support speculative diagnostic development. Amplitude growth within the boundary layer is $O(10^5)$ and we need to quantify the freestream where disturbances in the unstable pass band may be $O(10^{-7})$. We have to continue to develop the ideas of Fedorov [60] that look at not only thermal fluctuations as a least upper bound on freestream disturbances but freestream vorticity and surface roughness as well. These latter two have a profound effect on 3-D boundary layers.

Transition is a difficult problem and support must be continuous. The students that are graduated must be encouraged and supported to keep working in the area.

2. EXPERIMENTAL FACILITIES, DIAGNOSTICS, AND RESULTS

The objective of the foundational experiments was to perform fundamental experiments coordinated with theoretical and numerical requirements. The outcome of this work was to provide a comprehensive experimental map of the hypersonic transition parameter space and establish a database of mechanisms and growth rates in quiet flow. Considerable effort was also placed on facility and instrumentation development. The experimental accomplishments are listed below:

(1) Facility and Instrumentation Advancement
   a. Re-establishment and calibration of the Mach 6 Quiet Tunnel at TAMU
   b. Incorporation of novel optical diagnostics in the calibration of the Caltech T5 tunnel
   c. Calibration of the TAMU ACE Hypersonic Tunnel
   d. Further development of the laser-based VENOM diagnostic
   e. Design and construction of the TAMU Mach 5 shock tunnel
   f. Development of the focused schlieren technique (FST) and implementation for nonlinear measurements and angle-of-attack alignment at TAMU.
   g. Development of the Focused Laser Differential Interferometry (FLDI) at Caltech.
   h. Design and fabrication of a blunt-body model

(2) Hypersonic Stability and Transition Measurements
   a. Second mode instability on the Langley 93-10 cone in the M6QT
   b. Second model instability under high-enthalpy conditions in T5
   c. Transient growth instability on a 5-degree cone in the M6QT
   d. Trip instability and transition in the ACE Tunnel
   e. Crosshatch roughness and pressure gradient effects in the TAMU High Re tunnel
   f. Characterize the freestream and boundary layer in T5 using FLDI.
   g. Apply the FST with bi-coherence to identify the higher harmonics in the transitional region as nonlinear interactions of the fundamental.

Collectively, the experimental efforts resulted in new experimental capabilities and carefully acquired databases for theoretical model development and validation. It is expected that these diagnostics will be adapted for use in other hypersonic facilities. A brief synopsis of the role of each PI is given below. Detailed descriptions are given in the attached volumes.

2.1 Quiet Tunnel Experiments (William Saric): Experiments relevant to flight require ground-test facilities with very low disturbance levels. To enable this work, the Mach 6 Quiet Wind Tunnel (M6QT), previously of NASA Langley Research Center, was reestablished within a new pressure-vacuum blowdown infrastructure at Texas A&M. A 40-second run-time at <u>constant</u> conditions enables detailed measurements for comparison with computation. The freestream environment was extensively characterized, with a large region of low-disturbance flow (0.05%) found to be reliably present for unit Reynolds numbers Re' up to 11×10^6 /m [76]

The first set of quiet flow experiments were performed by the Saric group on a 5º half-angle flared cone model at $Re' = 10\times10^6$ /m and zero angle of attack. For the study of the second-mode instability, well-resolved boundary-layer profiles of mean and fluctuating mass flux were acquired at several axial locations using hot-wire probes with a bandwidth of 330 kHz. The second mode instability was observed to undergo significant growth between 250 and 310 kHz. Mode shapes of the disturbance agree well with those predicted from linear parabolized stability equation (LPSE) computations. A 17% (40 kHz) disagreement is observed in the frequency for most-amplified growth between experiment and LPSE. Possible sources of the disagreement are discussed in the detailed volumes. The effect of small misalignments of the model is quantified experimentally. A focused schlieren deflectometer with high bandwidth (1 MHz) and high signal-to-noise ratio was employed to complement the hot-wire work. The second-mode fundamental at 250 kHz was observed, as well as additional harmonic content not discernible in the hot-wire measurements at two- and three-times the fundamental. A bi-spectral analysis showed that after sufficient amplification of the second mode, several nonlinear mechanisms become significant, including ones involving the third harmonic, which have not hitherto been reported in the literature [13, 76, 77, 78, 79, 80].

The are some nascent projects in the M6QT involving: (1) the 7º yawed straight cone for crossflow to go along with Reed's computations [127, 132]; (2) the 5º flared cone examine Klebanoff-type breakdown in transition as demonstrated by Fasel and Reed; (3) the cooled cone from Purdue to enhance transition. This work is moving at a snail's pace since sequestration.

The details of this work are contained in the Volume V supplement.

2.2 Diagnostics and Roughness Experiments (Rodney Bowersox): In addition to collaborating with the Saric group on the M6QT installation and the North group on the VENOM diagnostic, the Bowersox group developed and calibrated the Actively Controlled Expansion Hypersonic Wind Tunnel (ACE), which is a 0.23 x 0.36 m, variable Mach (5 – 8) facility. This tunnel was used for late stability and transitional measurements. The freestream mean flow uniformity was less than 0.5%. The freestream disturbance levels were found to vary from 0.15% to 1.5% depending Reynolds number. Also a new Mach 5 shock tunnel (0.13 m x 0.13 m nozzle exit) was developed to aid in porting the VENOM diagnostic to high-enthalpy impulse tunnels. Measurements were also made in the supersonic high-Reynolds-number tunnel operating at Mach 5 [87, 141, 143, 145, 146, 158].

NASA diamond ("pizza box") trips were used within a low-Reynolds-number boundary layer (Re_θ = 3700), which allows for DNS computations. Hot-wire and Pitot pressure measurements were acquired. Moving downstream of the trips, the peak RMS disturbance value grew in amplitude until saturation. After this point, the peak decreased in amplitude, spread throughout the boundary layer, and ultimately led to transition. Detailed measurements were then acquired in the late transitional/turbulent boundary layer. The power spectra followed the traditional power law, which verified that the length scales followed the behavior described by Kolmogorov. The profile was quantified across the boundary layer into the sublayer [17, 40, 156, 157].

The effects of crosshatch roughness ($k/\delta \approx 0.07$) and pressure gradient (I_p = -0.08 and -0.49) on a Mach 5 high Reynolds number (Re_θ = 40,000) turbulent boundary layer were quantified using high-resolution particle image velocimetry (PIV). The distortion and reorientation of the large-scale coherent motions is quantified through the determination of the integral length scale and local structure angle from two-point correlations. Detection of individual hairpin vortices through the swirling strength criterion λ_{ci} allows the population distribution of the turbulent eddies to be examined, along with the conditionally averaged hairpin structure. The reduced Reynolds stresses observed in the favorable pressure gradients is partially due to the attenuation of the local flowfield around the near-wall hairpin structures, mitigating the mechanism for "producing" turbulence. The rotational rate of the hairpin vortices, measured through the mean prograde swirling strength, was reduced for the favorable pressure gradient models [2, 87, 122, 123, 124, 125].

The details of this work are contained in the Volume I supplement.

2.3 Blunt-Body Experiments (Eli Reshotko with Bowersox, Hornung, and Reed): A blunt-body model, in the shape of the MSL, was fabricated for determining the effect of roughness at angle of attack. Blockage tests were successfully completed in ACE. This work was scheduled for the last half-year of the center but as mentioned earlier, the project was terminated.[93, 110, 258, 260, 263, 264]

2.4 Diagnostics (Simon North): The North group worked to advance the Vibrationally Excited Nitric Oxide Monitory (VENOM) diagnostics, which combines two-line Planar Laser Induced Fluorescence methods and two-component Molecular Tagging Velocimetry. The technique monitors the nascent NO(v"=1) arising from photo-dissociation of trace amounts of NO_2 as a molecular tracer. The VENOM technique is expected to be not only applicable to cold high-speed flows, which is the focus of the present work, but also to combustion and other reactive or high-enthalpy flow fields. During this program, the spatial resolution was refined to 0.3 mm, with a velocity and temperature uncertainty of 1% and 5%, respectively. In addition, a new hypersonic flow apparatus was developed for advanced laser diagnostics development. This apparatus is characterized by its pulsed operation mode that translates into a significant reduction in mass flow rates and can be operated for long periods at Mach numbers ranging from 2.8 to 6.2. The flow conditions during the uniform flow time interval of each pulse vary by less than 1%, generating a flow of sufficient quality for quantitative measurements [15, 16, 32, 33, 34, 83].

The details of this work are contained in the Volume VI supplement.

2.5 Transient Growth Experiments (Edward White): The White group performed the second major experiment in the M6QT. This study focused on quantifying the effects of surface roughness on boundary-layer disturbance growth and laminar-to-turbulent transition. The transient growth mechanism that produces algebraic growth of streamwise streaks via decaying streamwise vortices has not previously been deliberately observed in hypersonic flow. The measurements were performed on in the boundary layer on a 5° half-angle smooth cone fitted with a slightly blunted nosetip and a ring of 18 periodically-spaced cube-like discrete roughness elements 1-mm tall by 1.78-mm wide by 1.78-mm long. The roughness element height was approximately equal to the boundary-layer thickness, yet no transition to turbulence is observed for freestream unit Reynolds numbers between 7.5×10^6 /m and 9.8×10^6 /m. Pitot measurements revealed azimuthally-alternating high- and low-speed streaks growing downstream of the roughness. Large unsteadiness was measured in the roughness wake but decays downstream. The streamwise evolution of the steady and unsteady disturbance energy is consistent with low-speed observations of transient growth in the mid-wake region behind periodically-spaced cylindrical roughness elements. This experiment contains the first quantitative measurements of roughness-induced transient growth in a high-speed boundary layer [111, 147].

The details of this work are contained in the Volume IX supplement.

2.6 T5 Experiments at Caltech (Joseph Shepherd and Hans Hornung): The Caltech team focused on incorporating novel optical techniques to quantify the freestream disturbances in T5 and second mode instability growth on a slender-body under hypervelocity conditions, which is a previously unexplored regime where thermochemical effects are important [14]. Narrowband disturbances (0.5-3.0 MHz) are measured in boundary layers with edge velocities of up to 5 km/s at two points along the generator of a 5 degree half angle cone. The freestream disturbances were found to be order 0.1% in the second-mode passband [12, 28]. Experimental amplification factor spectra were acquired. Linear stability and PSE analysis was performed, with fair prediction of the frequency content of the disturbances; however, the analysis over-predicts the amplification of disturbances. The results of this work have two key implications: 1) the acoustic instability is present and may be studied in a large-scale hypervelocity reflected-shock tunnel, and 2) these data provide a new basis on which the instability can be studied [45, 81, 82, 116, 120].

The development of the focused laser differential interferometry (FLDI) technique was certainly one of the highlights of the center [27, 117, 118, 121]. This permitted high bandwidth measurements in both the freestream and the boundary layer of T5 with the result that there is very little spectral content in the freestream disturbances in the range of 1 – 2 MHz. This is the second-mode (Mack mode) range for high enthalpy (high speed) boundary layers. The implications are huge in that this (amongst other things of course) probably accounts for the success of the porous coatings laminar flow control [3, 4, 8].Laminar flow control using CO2 injection was also studied. [89, 90, 91, 92, 105, 164]. It is fair to say that these are promising areas of further study.

The details of this work are contained in the Volume VII supplement.

3. THEORETICAL AND COMPUTATIONAL MODELLING

Over the past decades of studying stability and transition, it has become apparent that it is critically important for computations and experiments to work very closely together on the same geometries and operating conditions. Advances in basic mechanisms and prediction methods have come from working together. Transition is highly sensitive to operating conditions, especially in the hypersonic range. Computations provide validation of experiments and vice versa [30, 134, 135, 136, 137].

3.1 NPSE Calculations – Verification & Validation (Helen Reed): Within the NHSC, the computational group of Helen Reed has been collaborating with the other investigators and providing two-way verification and validation of findings, and a bridge from receptivity to the nonlinear stages of transition. The objectives were to extend the existing analytical framework beyond Mack's linear stability formulation to include relevant 3-D hypersonic flow physics, including identifying the relevant instabilities and interactions, carefully validating the predictive tools created, and disseminating these tools once validated. This group has been modeling attachment-line problems, Mack-mode instabilities, and crossflow instabilities, including on yawed/unyawed straight and flared cones, and more recently on elliptic cones.

Part 1: Attachment-line heating/cooling in a compressible flow [31, 133] was studied for mainly laminar flow control issues with the idea of either enhancing or ameliorating one (little studied) fundamental instability on swept wings and elliptic cones. Only modest temperature differences are needed to affect this instability.

Part 2: JoKHeR: NPSE simulations of hypersonic crossflow instability were developed [97, 98, 126, 131]. It was immediately apparent that an in-house code was required for prediction of unstable waves with inhomogeneous boundary conditions. This code has been used for virtually all of the TAMU stability calculations. It also supports the on-going experimental work in the M6QT on nonlinear breakdown of Mack modes.

Part 3: Instabilities on a 7º hypersonic yawed straight cone are concerned principally with crossflow instabilities and this work supports the nascent experimental work in the M6QT [127, 132].

Part 4: Boundary-layer instability and transition on a flared cone [96].

Part 4a: Boundary-layer instability and transition on a flared cone in a Mach 6 quiet wind tunnel [79]

Part 4b: Stability of hypersonic compression cones [126].

Part 4c: Hypersonic stability analysis of a flared cone [96].

Part 5: Verification and validation Issues in hypersonic stability and transition prediction [134].

The details of this work are contained in the Volume IV supplement.

3.2 Transition Modelling (Sharath Girimaji): The objectives of the Girimaji group's research was to incorporate their unique research in scalar transport in turbulent flows to later stages of boundary layer transition with the idea of bridging backward from low-Reynolds-number turbulence to the later stages of transition.

Part 1a: Instability mechanisms in hypersonic shear flows. In incompressible flows, pressure is a Lagrange multiplier with the sole purpose of imposing the divergence-free constraint on the velocity field. In high speed flow, pressure is a *bona fide* thermodynamic variable that evolves according to a wave equation derived from conservation of energy and state equations. This wave behavior of pressure introduces new flow mechanisms that strongly influence flow stability, transition and ultimately turbulence. The objective of this portion of work is to examine and explain the *pressure-based* mechanisms that lead to flow stabilization in hypersonic flows [36, 37, 38, 46].

Part 1b: Three-stage Instability Mechanism: Examination of the linearized perturbation equations reveals that the pressure-field evolution exhibits three distinct regimes in a hypersonic shear flow. In the first regime, the timescale of shear is much larger than that of pressure evolution. This leads to perturbation velocity field evolution purely according to the dictates of production mechanism. The second regime represents the state in which the shear and pressure timescales are comparable. Under these conditions, the shear-normal velocity and pressure fields interact as in a harmonic oscillator and yield and negative production. The production is nearly zero when integrated over each acoustic cycle causing the perturbations to be stabilized. In the third regime, the acoustic timescale is smaller than that of shear and the instabilities evolve in a manner similar to that in incompressible turbulence [1, 23].

Part 1c: Perturbation Obliqueness effects: Velocity-pressure dynamics of individual perturbation/fluctuation modes is investigated using direct numerical simulations and linear analysis in high Mach number homogeneous shear flow. For a given perturbation wave mode, the action of pressure is shown to depend on two important factors: the orientation of the wave vector with respect to the shear plane and modal Mach number. It is shown that the streamwise perturbation wave modes rapidly develop high level of dilatation but are self-limiting due to the action of pressure. On the other hand, spanwise perturbation wave modes develop purely solenoidal velocity fluctuations and are unaffected by pressure or Mach number. Oblique modes (oblique orientation with shear plane) combine solenoidal and dilatational characters and are shown to be chiefly responsible for stabilizing effects seen in engineering flows. Three regimes of obliqueness of different stability characteristics are identified. The investigation also isolates the linear, non-linear, inertial and pressure contributions in an attempt toward a comprehensive explanation of compressibility effects in high Mach number shear flows. The effects of linear and quadratic velocity profiles have been examined in detail.

Part 1d: Possible instability control mechanism: The key role played by pressure in compressible flows presents new avenues for the formulation of novel control strategies for controlling instability growth. Such control strategies can have foundations in the energy equation and exploit the strong coupling between momentum and energy balance equations It is demonstrated that `equi-partition’ of kinetic and potential energy' observed in second stage of growth of kinetic energy observed in sheared flow can be exploited to bring about the flow control. The so-called potential energy of turbulence resides in the fluctuating dilatational pressure and exchanges energy with dilatational kinetic energy through the pressure dilatation term. If we can devise control mechanisms to drain energy from potential energy through thermodynamic or acoustic means, then the level of wall normal velocity will also decrease significantly. Since the production of turbulence in shear flows is highly dependent on this component of velocity fluctuation, the subsequent growth of fluctuations will be substantially reduced.

Part 1e: Breakdown toward turbulence: It is demonstrated that breakdown toward turbulence is significantly delayed in hypersonic shear flows due to the suppression of spanwise vortical structures. This effect is brought about by the action of pressure in Regime-2 as described above. It is shown that non-linear interactions produce both streamwise and spanwise vortical structures at higher harmonics. The streamwise vortical structures grow unimpeded by compressibility effects but cannot by themselves lead to breakdown toward turbulence. It is shown that at later times, high-wavenumber low-Mach number spanwise vortical structures appear due to non-linear effects. The combination of these high-harmonic spanwise vortices and streamwise vortices ultimately leads to breakdown toward turbulence.

Part 2: Gas Kinetic Scheme for hypersonic non-equilibrium flows

Part 2a: Gas kinetics-based Numerical scheme for hypersonic non-equilibrium flows: The recently developed Gas Kinetic Method (GKM) for fluid flow computations is enhanced with advanced reconstruction (interpolation) schemes to enable direct simulation of highly compressible turbulent fields. Variants of Weighted essentially non-oscillatory (WENO) reconstruction schemes of different orders of accuracy are implemented and examined along with the more elementary van Leer method. The different schemes are evaluated for their accuracy, efficiency and numerical stability. The computed results are compared against the rapid distortion theory (RDT) for the case of compressible shear turbulence and `pressure-released' Burgers solution at high enough Mach numbers. In the case of decaying isotropic turbulence, the efficacy of the reconstruction schemes is evaluated by comparison against a `gold standard' high resolution simulation. The capabilities of the reconstruction schemes to capture linear, non-linear, pressure-released and viscous flow physics as well as solenoidal and dilatational features of the flow fields are established in isolation and combination. The most suitable WENO variant for integration with GKM is identified. Another important outcome of the study is the finding that temperature-interpolation is superior to energy-interpolation during the process of information transfer from cell-center to cell-interface. Overall, this work advances the applicability of kinetic theory based GKM to a wider range of high Mach number flow physics, specifically hypersonic boundary layers [20, 23, 46].

Part 3: Reduced chemical kinetics modeling for hypersonic flow applications

In external hypersonic flows, viscous and compressibility effects generate very high temperatures leading to significant chemical reactions among air constituents. Therefore, hypersonic flow computations require coupled calculations of flow and chemistry. Accurate and efficient computations of air-chemistry kinetics are of much importance for many practical applications but calculations accounting for detailed chemical kinetics can be prohibitively expensive. In this work, we investigate the possibility of applying chemical kinetics reduction schemes for hypersonic air-chemistry. We consider two chemical kinetics sets appropriate for three different temperature ranges: 2500K to 4500K; 4500K to 9000K; and above 9000K. By demonstrating the existence of the so-called the slow manifold in each of the chemistry sets, we show that judicious chemical kinetics reduction leading to significant computational savings is possible without much loss in accuracy [11, 88].

The details of this work are contained in the Volume III supplement.

3.3 Foundational Analysis and Control (Anatoli Tumin and Alexander Fedorov): As part of the *physics-based* approach, it was recognized early on that a fundamental foundation was necessary for the understanding of the "second-mode" (or Mack mode) and as well as the role of chemistry. Analytical and computational approaches were used to address these issues.

1. Mode terminology has been clarified and a new framework introduced. The "second mode" is not really a second mode in the sense of a discrete spectrum of eigenvalues and eigenfunctions and the group agreed that "fast" mode and "slow" mode are better descriptions. However, the notion of second mode is so ingrained in the community it may be hopeless to try to affect a change. A meaningful compromise would be to refer to the second mode as the Mack mode [7].
2. A tool has been developed for the projection of the solution of the linearized Navier-Stokes equations in reacting high speed boundary layers onto discrete modes.
3. Employed multi-mode decomposition to filter out the unstable mode from DNS and compared the result with a theoretical prediction based on the method of multiple scales that includes the nonparallel flow effects (in collaboration with X. Wang and X. Zhong).
4. Utilized PSE approximation to study the discrete mode branching (in collaboration with Y. Lifshitz and D. Degani [25] and P. Balakumar [222]). This was an important result in that PSE will always stick with the correct mode and the discrete branching may be difficult to interpret for the non-specialist.
5. Developed boundary layer solvers for binary mixtures and 5-species air.
6. A code for stability analysis including viscosity and real gas effects has been developed. It was shown that the spectrum with real gas effects is similar to the spectrum in a calorically perfect gas.
7. It was shown that an inviscid stability analysis captures main features of the spectrum and eigenfunctions. The real-gas effects considered for adiabatic, non-catalytic and partially-catalytic walls could be interpreted in terms of the wall-temperature effect for the second mode. Behavior of the mass fraction perturbation is governed by the mean flow mass fraction gradient and the vertical velocity perturbation. Perturbation of the chemical source term is significant for the second mode only in the vicinity of the wall, and it results in a change in the eigenvalues. The chemical source perturbation plays a stabilizing role, and the mechanism is governed by the physics in the vicinity of the wall.
8. A method for solving receptivity problems in presence of real-gas effects has been formulated. The considered examples indicate that there is an effect due to the branch points of the discrete spectrum similar to that in the calorically perfect-gas analysis.

9. The theoretical model of the second mode stabilization by porous coatings has been successfully validated by DNS and experiments [3, 4, 8, 55, 61, 107]. Guidelines for the choice of optimal porosity parameters have been formulated [50]. The porous coating laminar flow control technology has been developed to the readiness level suitable for flight tests.
10. The theoretical model [60] of boundary-layer receptivity to thermal fluctuations has been developed to estimate for the upper bound of transition Reynolds numbers in cases of "absolutely quiet" free stream and smooth bodies, where the forcing source is associated with indispensable thermal fluctuations (Brownian motion) only.
11. Theoretical models of supersonic [9] and hypersonic [56] boundary-layer receptivity to solid particulates (such as dust and aerosols) has been developed. The analytical solutions shed light on receptivity mechanism and provide foundation for prediction of particle-induced transition in high-altitude flights, where particulates can be the major forcing source. This mechanism may also be important for transition in wind tunnels and ballistic ranges unless special filtering techniques are employed.
12. It was demonstrated [62] that the amplitude method, which is a rational physics-based method for transition predictions, can be implemented for certain high-speed configurations including: T-S or second-mode dominated transition induced by thermal fluctuations; second-mode dominated transition induced by solid particulates; C-F dominated transition induced by small local and/or distributed roughness on a supersonic swept wing. The linear receptivity models were developed [9, 60, 63, 64] to evaluate the initial spectrum of unstable waves, the asymptotic theory was used to predict the downstream propagation of boundary-layer disturbances, and empirical amplitude criteria were used to predict the transition onset location. It was shown that, in the foregoing cases, the amplitude method can be realized on economical basis with keeping the numerical requirements nearly the same as for the e^N method. This effort was aimed to motivate the transition study groups to integrate their knowledge and tools in a rational framework of the amplitude method.

The details of this work are contained in the Volume VIII supplement.

3.4 Spatial DNS of Breakdown (Hermann Fasel): The research group of Fasel investigated laminar-turbulent transition using high-fidelity direct numerical simulations. The objective was to conduct DNS in close collaboration with other experimental and computational efforts to identify relevant mechanisms, especially the nonlinear breakdown mechanisms [54, 73]

The calculations of nonlinear wave interactions [99, 153, 154, 155], the Gaster wave packet [149,150, 151, 152] and turbulent spot [148] in a hypersonic boundary layer were remarkable because of the similarities with incompressible flow. This offers some promise that tackling the breakdown of hypersonic boundary layers is not as formidable as once thought. It makes sense. The second mode is a 2-D wave as is a T-S wave. The nonlinear interactions with background or forced 3-D modes produces a lambda vortex structure in the same way as Klebanoff-type breakdown in incompressible flow. The wall streaks have been observed in the Purdue Ludwig Tube using TSP and in the M6QT at A&M using IR Thermography. These features are presently being investigated in the M6QT. The similarities of the wave-packet calculations and turbulent spot calculations with the incompressible boundary layer are very encouraging. It seems as though we have a foundational starting point for the breakdown of hypersonic boundary layers.

For modeling the porous wall, a novel immersed boundary method was developed and implemented into the in-house developed compressible Navier-Stokes solver. With the new scheme it was possible to capture the effects of destabilization through very narrow porous coatings as predicted by theoretical studies by Fedorov. The results suggested that the viscous dissipation and the pressure diffusion play a major role in the stabilization/destabilization process and are at least one order of magnitude larger than the remaining terms computed in this study. In addition, simulations into the nonlinear transition regime revealed that the porous wall considerably delayed the breakdown to turbulence. [49,73,74,75]. These calculations are complementary to Fedorov's work in section (3.3).

Linearized Navier-Stokes were used to include chemical equilibrium in the boundary-layer stability calculations [139].

The details of this work are contained in the Volume II supplement.

3.5 Surface Roughness and Receptivity (Xiaolin Zhong): In addition to the later stages of transition work of Fasel, two other areas were recognized as requiring full DNS i.e. surface roughness and receptivity. These are summarized in the Annual Rev. Fluid Mech. Article [47]

Developed algorithms for surface roughness [5].

Examined laminar flow control using 2-D roughness [6, 10, 66, 67, 68]

Examined the receptivity of freestream disturbances to hypersonic boundary layers [24, 41, 43, 44, 84, 85, 86, 100-104, 159, 160, 171, 176, 180, 181].

Contributed to boundary-layer control using porous coatings [42, 165, 167, 169,170, 172, 174, 177, 179]. This work is complementary to the work described in (3.3) and (3.4). Thus, control of the second mode is much better understood. All that remains is some careful experiments in the M6QT.

Examined real-gas and surface-ablation effects on hypersonic boundary layer stability [112-115, 166, 168, 173, 178]. This work is complementary to the work in (3.1), (3.2), (3.3), and (3.4).

The details of this work are contained in the Volume X supplement.

4. STUDENTS AND PUBLICATIONS

During the period of operation the Center supported 41 PhD (14 graduated); 37 MS (19 graduated); 17 undergraduates; 12 Post-Docs. Sequestration left 25 students unsupported.

During four and one-half years of center operations, there were 47 journal publications; 130 conference proceedings; 31 abstracts; 64 oral presentations.

Journal articles:

1. Bertsch RL, Suman S, Girimaji SS. 2012. Rapid distortion Analysis of homogeneous shear flows: Characterization of flow-thermodynamics regimes. *Phys. Fluids*, 24(12)

2. Bowersox R, North S. 2010. Algebraic turbulent energy flux models for hypersonic shear flows. *Progr. Aero. Sci.*, 46:49-61

3. Brès GA, Colonius T, Fedorov AV. 2010. Acoustic properties of porous coatings for hypersonic boundary-layer control. *AIAA J*. 48(2):267-74

4. Brès GA, Inkman M, Colonius T, Fedorov AV. 2013. Second-mode attenuation and cancellation by porous coatings in a high-speed boundary layer. *J. Fluid Mech.*, 726:312-37

5. Duan L, Wang X, Zhong X. 2010. A high-order cut-cell method for numerical simulation of hypersonic boundary-layer instability with surface roughness. *J. Computational Physics* 229(19):7207-37

6. Duan L, Wang X, Zhong X. 2013. Stabilization of a Mach 5.92 boundary layer by two-dimensional finite-height roughness. *AIAA J*. 51(1):266-70

7. Fedorov A, Tumin A. 2011. High-speed boundary-layer instability: Old terminology and new framework. *AIAA J.* 49(8) 2011:1647-57

8. Fedorov A. 2011. Transition and stability of high-speed boundary layers. *Annu. Rev. Fluid Mech.*, 43:79-95

9. Fedorov A. 2013. Receptivity of a supersonic boundary layer to solid particulates. *J. Fluid Mech*. 37:105-31

10. Fong KD, Wang X, Zhong X. 2014. Numerical Simulation of Roughness Effect on the Stability of a Hypersonic Boundary Layer. *Computers and Fluids*, pp. 1-18

11. Girimaji SS, Ibrahim A. 2014. Advanced Quasi-Steady State Approximation for chemical kinetics. *Journal of Fluids Engineering* 136(3):031201

12. Hornung HG, Parziale NJ. 2010. Reflected shock tunnel noise control. In: Problems and achievements in applied mathematics and mechanics. Collection of works dedicated to 70th anniversary of academician V.M. Fomin (in Russian). Parallel, 2010, Novosibirsk. ISBN 978-5-98901-080-6, pp. 175-82

13. Hofferth JW, Saric WS, Kuehl J, Perez E, Kocian T, Reed HL. 2013. Boundary-layer instability and transition on a flared cone in a Mach 6 quiet wind tunnel. *Int. J. of Engineering Systems Modelling and Simulation* **5**(1/2/3) pp.109-24

14. Hornung HG. 2010. Deriving features of reacting hypersonic flow from gradients at a curved shock. *AIAA J.* 48(2):287-96

15. Hsu A, Srinivasan R, Bowersox R, North S. 2009. Application of molecular tagging towards simultaneous vibrational temperature and velocity mapping in an underexpanded jet flowfield. *AIAA J.* 47(1):2597-2604

16. Hsu A, Srinivasan R, Bowersox R, North, S. 2009. Two-component molecular tagging velocimetry utilizing NO fluorescence lifetime and NO2 photodissociation techniques in an underexpanded jet flowfield. *Applied Optics*, 48(22):4414–23

17. Humble R, Peltier S, Bowersox RDW. 2012. Visualization of the effects of convex curvature on the outer structure of a hypersonic turbulent boundary layer. *Phys. Fluids*, 24(10):24-48

18. Humble RA, Craig SA, Hofferth JW, Saric, WS. 2013. Spatiotemporal characterization of a millimetric annular dielectric barrier discharge plasma actuator. *Phys. Fluids*, 25(1), 017103

19. Karimi M, Girimaji SS, Gomez CA. 2012. Algebraic Reynolds stress and scalar flux modeling for compressible mixing layer. In *Proceedings of the 7th International Symposium on Turbulence Heat and Mass Transfer (THMT'12).* Palermo, Italy. K. Hanjalić, Y. Nagano and S. Jakirlić (Editors)

20. Kumar G, Girimaji SS. 2013. WENO-enhanced Gas Kinetic Method for highly compressible transition and turbulence simulations. *J. of Computational Physics* 234(1):499-523
21. Laurence SJ, Parziale NJ, Deiterding R. 2012. Dynamical separation of spherical bodies in supersonic flow *J. Fluid Mech.* 713 pp. 159-82
22. Lavin T, Girimaji SS, Suman S, Yu H. 2012. Flow-thermodynamics interactions in rapidly-sheared compressible turbulence. *Theoretical and Comp. Fluid Dynamics*, 26(6):501-22.
23. Lee KC, Girimaji SS. 2013. Flow-thermodynamics interactions in decaying anisotropic compressible turbulence with imposed temperature fluctuations. *Theoretical and Computational Fluid Dynamics*. 27(1-2):115-131
24. Lei J, Zhong X. 2012. Linear stability analysis of nose bluntness effects on hypersonic boundary layer transition. *J. of Spacecraft and Rockets*, 49(1):24-37
25. Lifshitz Y, Degani D, and Tumin A. 2012. Study of discrete modes branching in high-speed boundary layer. *AIAA J.* 50(10):2202-10
26. Parziale NJ, Rabinovitch J, Blanquart G, Hornung HG, Shepherd JE. 2013. A proposed vertical expansion tunnel. Under consideration. *AIAA J.* 55(12):2792-99
27. Parziale NJ, Shepherd JE, Hornung HG. 2012. Differential interferometric measurement of instability in a hypervelocity boundary Layer. *AIAA J*. 51(3):750-54
28. Parziale NJ, Shepherd JE, Hornung. HG. 2014. Free-stream density perturbations in a reflected-shock tunnel. *Exp Fluids*, 55(2):1665
29. Prakash A, Parsons N, Wang X, Zhong X. 2011. High-order shock-fitting methods for direct numerical simulation of hypersonic flow with chemical and thermal nonequilibrium. *J. Computational Physics*, 230:8474-507
30. Reed HL, Perez E, Kuehl J, Kocian T, Oliviero N. 2014. Verification and validation issues in hypersonic stability and transition prediction. Invited and accepted *Hypersonic Special Section, AIAA J. Spacecraft and Rockets*.
31. Reed HL, Saric WS. 2014. Attachment-line heating in a compressible flow. Invited *J. Engineering Mathematics, Milton Van Dyke Memorial Issue* 84(1): 99-110, DOI 10.1007/s10665-013-9662-5, link.springer.com.
32. Sanchez-Gonzalez R, Srinivasan R, Bowersox R, North, S. 2011. Simultaneous velocity and temperature measurements in gaseous flow fields using the VENOM technique. *Optics Letters*, 36(2)
33. Sanchez-Gonzalez R, Srinivasan R, Bowersox R, North, S. 2012. Simultaneous velocity and temperature measurements in gaseous flowfields using the vibrationally excited nitric oxide monitoring technique: a comprehensive study *Applied Optics*. 51:1215
34. Sanchez-Gonzalez R, Srinivasan R, Hofferth JW, Kim D, Tindall A, Bowersox RDW, North S. 2012. Repetitively pulsed hypersonic flow apparatus for diagnostic development. *AIAA J.* 50(3):691-97
35. Sanderson SR, Austin JM, Liang Z, Pintgen F, Shepherd JE, Hornung HG. 2010. Reactant Jetting in Unstable Detonation. *Progress in Aerospace Sciences*, 46(2-3):116-31.

36. Suman S, Girimaji SS, Bertsch R**.** 2009. Homogeneously-sheared compressible turbulence at the rapid distortion limit. *Proceedings of the 6th International Symposium on Turbulence Heat and Mass Transfer (THMT'09).* Rome, Italy. K. Hanjalić, Y. Nagano and S. Jakirlić (Editors) **–** 2009

37. Suman S, Girimaji SS. 2010. Velocity gradient invariants and local flow-field topology in compressible turbulence. *J. of Turbulence,* 11(2):1-24

38. Suman S, Girimaji SS. 2012. Velocity gradient dynamics in compressible turbulence: Influence of Mach number and dilatation rate. *J. of Turbulence*. 13:1-23

39. Suman S, Girimaji SS. 2013. Velocity-gradient dynamics in compressible turbulence: Characterization of Pressure-Hessian Tensor. *Physics of Fluids,* 25(12):125103

40. Tichenor N, Humble R, Bowersox RDW. 2013. Response of hypersonic turbulent boundary layer to favorable Pressure Gradients. *J. Fluid Mech.* 722:187-213

41. Tumin A, Wang X, Zhong X. 2011. Numerical simulation and theoretical analysis of perturbations in hypersonic boundary layers. *AIAA J.* 49(3):463-71

42. Wang X, and Zhong X. 2012. The stabilization of a hypersonic boundary layer using local sections of porous coating. *Phys. Fluids,* 24(3), 034105

43. Wang X, Zhong X, Ma Y. 2011. Response of a Hypersonic Boundary Layer to Wall Blowing–Suction. *AIAA J.* 49(7):1336-53

44. Wang X, Zhong X. 2009. Effect of wall perturbations on the receptivity of a hypersonic boundary layer. *Physics of Fluids,* 21(4) 04410:1-19

45. Wen C, Hornung HG. 2010. Nonequilibrium recombination after a Curved Shockwave. *Progr. Aero. Sci.,* 46 (2-3):132-9

46. Xie Z, Girimaji SS. 2014. Linear stability of Poiseulle flow at extreme Mach numbers: Linear Analysis and Simulations. *Physical Review E* 89(4):043001

47. Zhong X, Wang X. 2012. Direct Numerical Simulation of Receptivity, Instability, and Transition of Hypersonic Boundary Layers. *Annu. Rev. Fluid Mech*, 44*:*527-61

Conference proceedings:

48. Berry SA, Kimmel R, Reshotko E. 2011. Recommendations for hypersonic boundary layer transition flight testing. *AIAA Pap. No. 2011-3415*

49. Brehm C, Hader C, Fasel H. 2012. Novel immersed boundary/interface method for the compressible Navier-Stokes equations. *AIAA Pap. No. 2012-1110*

50. Brès, GA, Inkman, M, Colonius T, Fedorov AV. 2009. Alternate designs of ultrasonic absorptive coatings for hypersonic boundary layer control. *AIAA Pap. No. 2009-4217*

51. Craig SA, Humble RA, Hofferth JW, Saric WS. 2011. Characterization of the flowfield structure of an annular dielectric barrier discharge plasma actuator. *AIAA Pap. No. 2011–3987*

52. Duan L, Wang X, Zhong X. 2009. A High-Order Cut-Cell Method for Numerical Simulation of Hypersonic-Boundary Transition with Arbitrary Surface Roughness. *AIAA Pap. No. 2009-1337*

53. Duan L, Zhong X. 2010. A High Order Cut Cell Method for Numerical Simulation of Three Dimensional Hypersonic Boundary-Layer Transition with Finite Surface Roughness. *AIAA Pap. No. 2010-1450*

54. Fasel H. 2012. Direct numerical simulation of laminar-turbulent transition for a cone at M = 6. RTO Specialists Meeting AVT-200/RSM-030 on Hypersonic Laminar-Turbulent Transition, San Diego

55. Fedorov A, Brès G, Inkman M, Colonius T. 2011. Instability of hypersonic boundary layer on a wall with resonating micro-cavities. *AIAA Pap. No. 2011-373*

56. Fedorov A, Kozlov M. 2011. Receptivity of high-speed boundary layer to solid particulates. *AIAA Pap. No. 2011-3925*

57. Fedorov A, Tumin A. 2010. Branching of discrete modes in high-speed boundary layers and terminology issues. *AIAA Pap. No. 2010-5003*

58. Fedorov A. 2012. Prediction of cross-flow dominated transition on a supersonic swept wing. *AIAA Pap. No. 2012-920*

59. Fedorov A. 2013. Theoretical modeling of TS-dominated transition induced by solid particulates. *AIAA Pap. No. 2013-0668*

60. Fedorov AV, Averkin, SN. 2009. Receptivity of compressible boundary layer to kinetic fluctuations. In *Proceedings of the 7th IUTAM Symposium on Laminar Turbulent Transition*, Stockholm, Sweden

61. Fedorov AV. 2010. Temporal stability of hypersonic boundary layer on porous wall. Comparison of theory with DNS. *AIAA Pap. No. 2010-1242*

62. Fedorov AV. 2012. Applications of the Mack Amplitude Method to transition predictions in high-speed flows. Presented at RTO Specialists Meeting AVT-200/RSM-030 on Hypersonic Laminar-Turbulent Transition, San Diego pp. 6-1-6-30

63. Fedorov AV. 2012. Prediction of cross-flow dominated transition on a supersonic swept wing. *AIAA Pap. No. 2012-0920*

64. Fedorov AV. 2013. Theoretical modeling of TS-dominated transition induced by solid particulates. *AIAA Pap. No. 2013-0668*

65. Fedorov, A, Ryzhov, A, Soudakov, V. 2011. Numerical and theoretical modeling of supersonic boundary-layer receptivity to temperature spottiness. *AIAA Pap. No. 2011-3077*

66. Fong KD, Wang X, Zhong X. 2012. Finite roughness effect on modal growth of a hypersonic boundary layer. *AIAA Pap. No. 2012-1086*

67. Fong KD, Wang X, Zhong X. 2012. Numerical simulation of roughness effect on the stability of a hypersonic boundary layer. Presented at Seventh Int. Conf. on Computational Fluid Dyn. (ICCFD7), Big Island, HI

68. Fong KD, Wang X, Zhong X. 2013. Stabilization of Hypersonic Boundary Layer by 2-D Surface Roughness. *AIAA Pap. No. 2013-2985*

69. Girimaji, SS. 2009. Current Status of Basic Research in Hypersonic Turbulence. Invited session on hypersonic turbulence. *AIAA Pap. No. 2009-151*

70. Gomez C, Girimaji SS. 2011. Algebraic Reynolds Stress Model (ARSM) for compressible shear flows**.** *AIAA Pap. No. 2011-3572*

71. Greene PT, Eldredge JD, Zhong X, Kim J. 2011. Numerical Study of Hypersonic Flow Over an Isolated Roughness with a High-Order Cut-Cell Method. *AIAA Pap. No. 2011-3249*

72. Greene PT, Eldredge JD, Zhong X, Kim J. 2014. Numerical Simulation of High-Speed Flows Over Complex Geometries with a High-Order Multi-Zone Cut-Cell Method. *AIAA Pap. No. 2014-0426*

73. Hader C, Brehm C, Fasel H. 2013. Numerical investigation of porous walls for a Mach 6.0 boundary layer using an Immersed Interface Method. *AIAA Pap. No. 2013-0829*

74. Hader C, Brehm C, Fasel H. 2013. Numerical investigation of transition delay using porous walls. *AIAA Pap. No. 2013-2740*

75. Hader C, Fasel H. 2011. Numerical investigation of porous walls for a Mach 6.0 boundary layer using an Immersed Boundary Method. *AIAA Pap. No. 2011-3081*

76. Hofferth JW, Bowersox RDW, Saric WS. 2010. The Mach 6 Quiet Tunnel at Texas A&M: quiet flow performance. *AIAA Pap. No. 2010–4794*

77. Hofferth JW, Humble RA, Floryan DC, Saric WS. 2013. High-bandwidth optical measurements of the second-Mode instability in a Mach 6 Quiet Wind Tunnel. *AIAA Pap. No. 2013-0378*

78. Hofferth JW, Saric WS, Kuehl J, Kocian T, Reed HL. 2012. Boundary-layer instability & transition on a flared cone in a Mach 6 quiet wind tunnel. RTO/*AVT Specialists Meeting on Hypersonic Laminar-Turbulent Transition: AVT-200/RSM-030*, San Diego, Pap. No. 10 16-19

79. Hofferth JW, Saric WS, Kuehl J, Perez E, Kocian T, Reed HL. 2012. Comparison of experimental and computational boundary-layer profiles and instability growth on a flared cone in a Mach 6 quiet flow. *3AF Pap. No. 37 FP37-2012*

80. Hofferth JW, Saric WS. 2012. Boundary-layer transition on a flared cone in the Texas A&M Mach 6 Quiet Tunnel. *AIAA Pap. No. 2012-0923*

81. Hornung HG, Parziale NJ. 2013. Spectral characteristics of Pitot noise. *Int. Symp. on Shock Waves, 29th*, Madison

82. Hornung HG, Schramm JM, Hannemann K. 2011. Sonic line and stand-off distance on re-entry capsule shapes. *Int. Symp. on Shock Waves, 28th*, Manchester, England, UK

83. Hsu A, Srinivasan R, Bowersox R, North S. 2009. Two-component molecular tagging velocimetry utilizing NO fluorescence lifetime and NO2 photodissociation techniques in an underexpanded jet flowfield. *AIAA Pap. No. 2009-4049*

84. Huang Y, Zhong X. 2010. Numerical Study of Laser-Spot Effects on Boundary-Layer Receptivity for Blunt Compression-Cones in Mach-6 Freestream. *AIAA paper 2010-4447*

85. Huang Y, Zhong X. 2011. Numerical Study of Freestream Hot-Spot Perturbation on Boundary-Layer Receptivity for Blunt Compression-Cones in Mach-6 Flow. *AIAA Pap. No 2011-3078*

86. Huang Y, Zhong X. 2012. Numerical study of boundary-layer receptivity on blunt compression-cones in Mach-6 flow with localized freestream hot-spot perturbations. *RTO/AVT Specialists Meeting on Hypersonic Laminar-Turbulent Transition: AVT-200/RSM-030*, San Diego

87. Humble R, Peltier, S, Lynch K, Thuro, B, Bowersox RDW. 2011. Visualization of hypersonic turbulent boundary layers negotiating convex curvature. *AIAA Pap. No. 2011-3419*

88. Ibrahim A, Suman S, Girimaji SS. 2011. On the use of reduced chemical kinetics for hypersonic transition and breakdown to turbulence computations. *AIAA Pap. No. 2011-3715*

89. Jewell JS, Leyva IA, Parziale NJ, Shepherd JE. 2011. Effect of gas injection on transition in hypervelocity boundary layers. *Int. Symp. on Shock Waves, 28th*, Manchester, England, UK

90. Jewell JS, Leyva IA, Shepherd JE. 2013. Parameters for transition on a 5-degree half-angle cone in hypervelocity flow. *Int. Symp. on Shock Waves*, *29th*, Madison

91. Jewell JS, Parziale NJ, Leyva IA, Shepherd JE. 2012. Turbulent spot observations within a hypervelocity boundary layer on a thin cone. *AIAA Pap. No. 2012-3036*

92. Jewell JS, Wagnild RM, Leyva IA, Candler GV, Shepherd JE. 2013. Transition within a hypervelocity boundary layer on a 5-degree half-angle cone in air/CO2 mixtures. *AIAA Pap. No. 2013-0523*

93. Karl S, Hannemann K, Hornung HG. 2011. Bluntness effects in hypersonic flow over slender cones and wedges. *Int. Symp. on Shock Waves, 28th*, Manchester, England, UK

94. Klentzman J, Tumin A. 2013. Stability and receptivity of high speed boundary layers in oxygen. *AIAA Pap. No. 2013-2882*

95. Klentzman J, Ulker E, Tumin A. 2012. Projection of the solution of the linearized Navier-Stokes equations in reacting high-speed boundary layer onto discrete modes. *AIAA Pap. No. 2012-3149*

96. Kocian T, Perez E, Oliviero N, Kuehl J, Reed HL. 2013. Hypersonic stability analysis of a flared cone. *AIAA Pap. No. 2013-0667*

97. Kuehl J, Perez E, Reed HL. 2012. JoKHeR: NPSE simulations of hypersonic crossflow Instability. *AIAA Pap. No. 2012-0921*

98. Kuehl J, Reed HL, Kocian T, Oliviero N. 2014. Nonlinear detuning of Mack-mode instabilities. *AIAA Pap. No. 2014-XXXX – June 2014.*

99. Laible A, Fasel H. 2011. Numerical investigation of hypersonic transition for a flared and a straight cone at Mach 6. *AIAA Pap. No. 2011-3565*

100. Lei J, Zhong X. 2009. Linear Stability Study of Hypersonic Boundary Layer Transition on Blunt Circular Cones. *AIAA Pap. No. 2009-939*

101. Lei J, Zhong X. 2010. Linear Stability Analysis of Nose Bluntness Effects on Hypersonic Boundary Layer Transition. *AIAA Pap. No. 2010-898*

102. Lei J, Zhong X. 2011. Non-linear Breakdown in Hypersonic Boundary Layer Transition Induced by Freestream Disturbances. *AIAA Pap. No. 2011-3563*

103. Lei J, Zhong X. 2012. Numerical study of freestream waves induced breakdown in hypersonic boundary layer transition. *AIAA Pap. No. 2012-2692*

104. Lei J, Zhong X. 2013. Numerical Simulation of Freestream Waves Receptivity and Breakdown in Mach 6 Flow over Cone. *AIAA Pap. No. 2013-2741*

105. Leyva I, Jewell JS, Laurence S, Hornung HG, Shepherd JE. 2009. On the impact of injection schemes on transition in hypersonic boundary layers. *AIAA Pap. No. 2009-7204*

106. Lifshitz Y, Degani D, Tumin A. 2012. Study of discrete modes branching in high-speed boundary layers. *AIAA Pap. No. 2012-0919*

107. Lukashevich SV, Maslov AA, Shiplyuk AN, Fedorov AV, Soudakov,VG. 2010. Stabilization of high-speed boundary layer using porous coatings of various thicknesses. *AIAA Pap. No. 2010-4720*

108. Marineau E, Hornung HG. 2010. Apollo-shaped capsule boundary layer transition at high-enthalpy in T5. *AIAA Pap. No.2010-446*

109. Marineau E, Hornung HG. 2010. Study of bow-shock wave unsteadiness in hypervelocity flow from reservoir fluctuations. *AIAA Pap. No. 2010-382*

110. Mitrea A, Parziale NJ, Jewell JS, Hornung HG, Shepherd JE. 2012. Time resolved heat-flux measurements on a CEV candidate shape at high enthalpy. *RTO Specialists Meeting AVT-200/RSM-030 on Hypersonic Laminar-Turbulent Transition*, San Diego

111. Monschke J, Kuester MS, White EB. 2013. Acoustic receptivity measurements using modal decomposition of a modified Orr–Sommerfeld equation. *AIAA Pap. No. 2013-0669*

112. Mortensen CH, Zhong X. 2012. High-order shock-fitting method for hypersonic flow with graphite ablation and boundary layer stability. *AIAA Pap. No. 2012-3150*

113. Mortensen CH, Zhong X. 2013. Numerical Simulation of Graphite Ablation Induce Outgassing Effects on Hypersonic Boundary Layer Receptivity over a Cone Frustum. *AIAA Pap. No 2013-0522*

114. Mortensen CH, Zhong X. 2013. Numerical simulation of graphite ablation induce outgassing effects on hypersonic boundary layer receptivity over a cone frustum. *AIAA Pap. No. 2013-0522*

115. Mortensen CH, Zhong X. 2013. Real Gas and Surface Ablation Effects on Hypersonic Boundary Layer Instability over a Blunt Cone. *AIAA Pap. No. 2013-2981*

116. Parziale NJ, Hornung HG, Shepherd JE. 2012. Optical detection of transitional phenomena in hypervelocity flow over slender bodies. RTO Specialists Meeting AVT-200/RSM-030 on Hypersonic Laminar-Turbulent Transition, San Diego

117. Parziale NJ, Hornung HG, Shepherd JE. 2012. Reflected shock tunnel noise measurement by focused differential interferometry. *AIAA Pap. No. 2012-3261*

118. Parziale NJ, Jewell JS, Shepherd JE, Hornung HG. 2011. Shock tunnel noise measurement with resonantly enhanced focused Schlieren deflectometry. *Int. Symp. on Shock Waves, 28th*, Manchester, England UK

119. Parziale NJ, Rabinovitch J, Blanquart G, Hornung HG, Shepherd JE. 2012. A proposed vertical expansion tunnel. *AIAA Pap. No. 2012-3263*

120. Parziale NJ, Shepherd JE, 2013. Geometric acoustics within a hypersonic boundary layer. *Int. Symp. on Shock Waves, 29th*, Madison

121. Parziale NJ, Shepherd JE, Hornung HG. 2013. Differential interferometric measurement of instability at two points in a hypervelocity boundary layer. *AIAA Pap. No. 2013-0521*

122. Peltier S, Bowersox R. 2010. Periodic surface roughness in high-speed turbulent flow. *AIAA Pap. No. 2010-5020*

123. Peltier S, Humble R, Bowersox R. 2011. Response of a hypersonic turbulent boundary layer to local and global mechanical distortions. *AIAA Pap. No. 2011-0680*

124. Peltier S, Humble R, Bowersox RDW. 2012. PIV of a Mach 5 turbulent boundary layer over diamond roughness elements. *AIAA Pap. No. 2012-3061*

125. Peltier S, Humble R, Bowersox RDW. 2012. The influence of favorable pressure gradients upon the coherent motions in a Mach 5 turbulent boundary layer. *AIAA Pap. No. 2012-3060*

126. Perez E, Kocian T, Kuehl J, Reed HL. 2012. Stability of hypersonic compression cones. *AIAA Pap. No. 2012-2962*

127. Perez E, Reed HL, Kuehl J. 2013. Instabilities on a hypersonic yawed straight cone. *AIAA Pap. No. 2013-2879*

128. Prakash A, Parsons N, Wang X Zhong X. 2010. High-order shock-fitting methods for hypersonic flow with chemical and thermal nonequilibrium. *AIAA Pap. No 2010-4997*

129. Prakash A, Zhong X. 2009. Numerical Simulation of Planetary Reentry Aeroheating over Blunt Bodies with Non-equilibrium Reacting flow and Surface Reactions. *AIAA Pap. No. 2009-1542*

130. Prakash A, Zhong X. 2012. Numerical simulation of receptivity of freestream disturbances to hypersonic boundary layers with thermochemical nonequilibrium. *AIAA Pap. No. 2012-1085*

131. Reed HL, Kuehl J, Perez E, Kocian T, Hofferth JW, Saric WS. 2012. Nonlinear parabolized stability equation simulations in hypersonic flows. *RTO/AVT Specialists Meeting on Hypersonic Laminar-Turbulent Transition: AVT-200/RSM-030*, San Diego

132. Reed HL, Perez E, Kuehl J, Kocian T, Oliviero N. 2013. Hypersonic stability and transition prediction. *AIAA-Pap. No. 2013-2556*

133. Reed HL, Saric WS. 2011. Attachment-line heating in a compressible flow. *AIAA-2011-3242*

134. Reed HL. 2011. Verification and validation in transition studies. *Keynote Address, International Workshop on Verification and Validation (V&V) in Computational Science*, University of Notre Dame

135. Reed HL. 2013. Hypersonic boundary-layer laminar-turbulent transition. Celebrating 60 Years of AFOSR: Hypersonics into the 21st Century: Research Progress since 2001 and Future Directions in Aerothermodynamics, 43rd AIAA Fluid Dynamics Conference, San Diego

136. Reed HL. 2013. Hypersonic stability and transition prediction. *AIAA-Pap. No. 2013-2556*

137. Reshotko E, Tumin A. 2012. *Technical evaluation report. Hypersonic laminar-turbulent transition. RTO/AVT Specialists Meeting on Hypersonic Laminar-Turbulent Transition: AVT-200/RSM-030*, San Diego

138. Rodriguez Alvarez D, Tumin A, Theofilis V. 2011. Towards the foundation of a global modes concept. *AIAA Pap. No. 2011-3603*

139. Salemi L, Fasel H. 2013. Linearized Navier-Stokes simulation of the spatial stability of a hypersonic boundary layer in chemical equilibrium. *AIAA Pap. No. 2013-2984*

140. Sanchez-Gonzalez R, Srinivasan R, Hofferth JW, Doyong K, Bowersox RDW, North S. 2012. Repetitively pulsed hypersonic flow apparatus for advanced laser diagnostic development. *AIAA Pap. No. 2012-0733*

141. Sanchez-Gonzalez R, Tindall A, Bowersox R, North S, Hsu A. 2010. Towards simultaneous velocimetry and thermometry measurements using the VENOM diagnostic technique. *AIAA Pap. No. 2010-4349*

142. Sanderson SR, Austin JM, Liang Z, Pintgen F, Shepherd JE, Hornung HG. 2009. Reactant Jetting in Unstable Detonation. (2010 Best Paper Award) *AIAA Pap. No. 2009-4325*

143. Saric WS, Reed, HL, Bowersox RD, North S. 2011. Hypersonic laminar-turbulent transition studies. *7th European Symposium on Aerothermodynamics for Space Vehicles,* Site Oud Sint-Jan, Bruges, Belgium

144. Schmidt B, Bobbitt B, Parziale NJ, Shepherd JE. 2013. Experiments in a combustion-driven shock tube with an area change. *Int. Symp. on Shock Waves, 29th, Madison*

145. Semper M, Pruski B, Bowersox, RDW 2012. Freestream turbulence measurements in a continuously variable hypersonic wind tunnel. *AIAA Pap. No. 2012-0732*

146. Semper M, Tichenor N, Bowersox R, Srinivasan R, North S. 2009. On the design and calibration of an actively controlled expansion hypersonic wind tunnel. *AIAA Pap. No. 2009-799*

147. Sharp N, White EB. 2014. Roughness-Induced Transient Growth on a Hypersonic Blunt Cone. *AIAA Pap. No. 2014-0432*

148. Sivasubramanian J, Fasel H. 2010. Direct numerical simulation of a turbulent spot in a cone boundary-layer at Mach 6. *AIAA Pap. No. 2010-4599*

149. Sivasubramanian J, Fasel H. 2010. Numerical investigation of boundary-layer transition initiated by a wave packet for a cone at Mach 6. *AIAA Pap. No. 2010-0900*

150. Sivasubramanian J, Fasel H. 2011. Numerical investigation of laminar-turbulent transition in a cone boundary layer at Mach 6. *AIAA Pap. No. 2011-3562*

151. Sivasubramanian J, Fasel H. 2011. Transition initiated by a localized disturbance in a hypersonic flat-plate boundary layer. *AIAA Pap. No. 2011-0374*

152. Sivasubramanian J, Fasel H. 2012. Growth and breakdown of a wave packet into a turbulent spot in a cone boundary layer at Mach 6. *AIAA Pap. No. 2012-0085*

153. Sivasubramanian J, Fasel H. 2012. Nonlinear stages of transition and breakdown in a boundary layer on a sharp cone at Mach 6. *AIAA Pap. No. 2012-0087*

154. Sivasubramanian J, Fasel H. 2013. Direct numerical simulation of controlled transition in a boundary layer on a sharp cone at Mach 6. *AIAA Pap. No. 2013-0263*

155. Sivasubramanian J, Laible A, Fasel H. 2011. Numerical simulation of transition in hypersonic boundary layers. DoD High Performance Computing Modernization Program Users Group Conference, Portland, OR

156. Tichenor N, Humble R, Bowersox R. 2011. Influence of favorable pressure gradients on a Mach 5.0 turbulent boundary layer. *AIAA Pap. No. 2011-0748*

157. Tichenor N, Humble R, Bowersox RDW. 2012. Reynolds stresses in a hypersonic boundary layer with streamline curvature-driven favorable pressure gradients. *AIAA Pap. No. 2012-3059*

158. Tichenor N, Semper M, Srinivasan R, Bowersox R, North S. 2010. Calibration of an actively controlled expansion hypersonic wind tunnel. *AIAA Pap. No. 2010-4793*

159. Tumin A, Wang X, Zhong X. 2009. Direct numerical simulation and theoretical analysis of perturbations in hypersonic boundary layers. *Proc. 7th IUTAM Symposium on Laminar-Turbulent Transition*, Stockholm, Sweden pp. 427-32

160. Tumin A, Wang X, Zhong X. 2010. Numerical simulation and theoretical analysis on hypersonic boundary-layer receptivity to wall blowing-suction. *AIAA Pap. No. 2010-0534*

161. Tumin A. 2009. Toward foundation of a global (bi-global) modes concept. In *Global Flow Instability and Control – IV*, Creta Maris, Hersonissos, Crete, (V. Theofilis, T. Colonius, A. Seifert eds.), ISBN-13: 978-84-692-6247-4

162. Tumin A. 2011. The biorthogonal eigenfunction system of linear stability equations: A survey of applications to receptivity problems and to analysis of experimental and computational results. *AIAA Pap. No. 2011-3244*

163. Ulker E, Klentzman J, Tumin A. 2011. Stability of boundary layers in binary mixtures of oxygen and nitrogen. *AIAA Pap. No. 2011-0370*

164. Wagnild R, Candler G, Leyva I, Jewell J, Hornung HG. 2010. Carbon dioxide injection for hypervelocity boundary layer stability. *AIAA Pap. No. 2010-1244*

165. Wang X Zhong X. 2010. Effect of porous coating on boundary-layer instability. *AIAA Pap. No. 2010-1243*

166. Wang X, Zhong X. 2011. Development and validation of a high-order shock-fitting non-equilibrium flow solver. *AIAA Pap. No. 2011-365*

167. Wang X, Zhong X. 2009. Effect of porous coating and its location on hypersonic boundary layer waves. *AIAA Pap. No. 2009-942*

168. Wang X, Zhong X. 2009. Nonequilibrium and reactive high-speed flow simulations with a fifth-order WENO scheme. *AIAA Pap. No. 2009-4041*

169. Wang X, Zhong X. 2009. Numerical simulation and theoretical analysis on boundary-layer instability affected by porous coating. *AIAA Pap. No. 2009-3679*

170. Wang X, Zhong X. 2010. The impact of porous surface on hypersonic boundary layer instability. *AIAA Pap. No. 2010-5021*

171. Wang X, Zhong X. 2010. Transient growth of a Mach 5.92 flat-plate boundary layer. *AIAA Pap. No. 2010-535*

172. Wang X, Zhong X. 2011. Numerical simulations on mode S growth over feltmetal and regular porous coatings of a Mach 5.92 flow. *AIAA Pap. No. 2011-375*

173. Wang X, Zhong X. 2011. DNS of strong shock and turbulence interactions including real gas effects. *AIAA Pap. No. 2011-3707*

174. Wang X, Zhong X. 2011. Phase angle of porous coating admittance and its effect on boundary-layer stabilization. *AIAA Pap. No. 2011-3080*

175. Wang X, Zhong X. 2012. A high-order shock-fitting non-equilibrium flow solver for DNS of strong shock and turbulence interactions. 2012. *Seventh Int. Conf. on Computational Fluid Dyn.* (ICCFD7), Big Island, HI

176. Wang X, Zhong X. 2012. Effect of compressibility on strong shock and turbulence interactions. *AIAA Pap. No. 2012-1243*

177. Wang X, Zhong X. 2012. Passive control of hypersonic boundary-layer transition using regular porous coating. *Seventh Int. Conf. on Computational Fluid Dyn.* (ICCFD7), Big Island, HI

178. Wang X, Zhong X. 2012. Thermochemical non-equilibrium effects on passive control of hypersonic boundary-layer transition using regular porous coating. *AIAA Pap. No. 2012-3256*

179. Wang X, Zhong X. 2013. The stabilization of a Mach 10 boundary layer using regular porous coating. *AIAA Pap. No. 2013-0827*

180. Zhong X. 2009. Numerical Simulation of Hypersonic Boundary Layer Receptivity and Stability on Blunt Circular Cones. *AIAA Pap. No. 2009-0940*

181. Zhong X, Lei J. 2011. Numerical Simulation of Nose Bluntness Effects on Hypersonic Boundary Layer Receptivity to Freestream Disturbances. *AIAA Pap. No. 2011-3079*

Abstracts:

182. Bertsch R, Girimaji SS. 2009. Pressure Effects in Compressible Flows at the Rapid Distortion Limit**.** *Bulletin of the American Physical Society* 54(19)

183. Bertsch RL, Girimaji SS, Kumar G. 2012. Direct numerical simulation of compressible Kolmogorov flow. *Bul. Amer. Phys. Soc.* 57(17)

184. Bertsch RL, Kumar G, Girimaji SS. 2011. Flow-thermodynamics interactions in compressible shear-driven turbulence: Linear analysis of possible flow control strategies. *Bul. Amer. Phys. Soc.* 56(18)

185. Craig SA, Humble RA, Hofferth JW, Saric WS. 2011. Flow-field characterization of DBD plasma actuators as discrete roughness elements for laminar flow control. *Bul. Amer. Phys. Soc.* 56(18)

186. Fedorov A. Tumin A. 2009. How many unstable modes are in high-speed boundary layers? *Bul. Amer. Phys. Soc.* 54(19)

187. Hofferth JW, Saric WS. 2010. Texas A&M Mach 6 Quiet Tunnel: quiet flow performance. *Bul. Amer. Phys. Soc.* 55(16)

188. Hofferth JW, Saric WS. 2011. Boundary-layer instability & transition on a flared cone in a Mach 6 quiet wind tunnel. *Bul. Amer. Phys. Soc.* 56(18)

189. Hofferth JW, Saric WS. 2012. Azimuthal hotwire measurements in a transitional boundary layer on a flared cone in a Mach 6 quiet wind tunnel. *Bul. Amer. Phys. Soc.* 57(17)

190. Ibrahim A, Girimaji SS. 2010. High-Order Quasi-Steady State Assumption for Chemistry Reduction. *Bul. Amer. Phys. Soc.* 55(16)

191. Jewell J, Wagnild R, Leyva I, Candler G, Shepherd JE. 2012. Transition within a hypervelocity boundary layer on a 5-degree half-angle cone in free stream air/CO2 mixtures. *Bul. Amer. Phys. Soc.* 57(17)

192. Karimi M, Girimaji SS. 2012. Linear analysis and temporal DNS of compressible mixing layers. *Bul. Amer. Phys. Soc.* 57(17)

193. Klentzman J, Tumin A. 2011. Receptivity of high-speed boundary layers with real gas effects. *Bul. Amer. Phys. Soc.* 56(18)

194. Klentzman J, Tumin A. 2012. Receptivity of high-speed boundary layers with real gas effects. *Bul. Amer. Phys. Soc.* 57(17)

195. Klentzman J, Tumin A. 2013. Stability of high-speed boundary layers in oxygen including chemical non-equilibrium effects. *Bul. Amer. Phys. Soc.* 58(18)

196. Klentzman J, Ulker E, Tumin A. 2010. Inviscid stability analysis of chemically reacting boundary layers in binary gas mixtures. *Bul. Amer. Phys. Soc.* 55(16)

197. Klentzman J, Ulker E, Tumin A. 2011. The role of the frozen relative Mach number on the stability of boundary layer in chemical non-equilibrium. *Bul. Amer. Phys. Soc.* 56(18)

198. Kumar G, Bertsch R, Girimaji SS. 2010. DNS and Rapid Distortion Theory investigations of Mach number effects on velocity- pressure field interactions in strongly sheared flows. *Bul. Amer. Phys. Soc.* 55(16)

199. Monschke J, White EB. 2013. Interpretations of Incompressible Continuous Spectrum Receptivity Curves for Transient Growth. *Bul. Amer. Phys. Soc.* 54(19)

200. Parziale NJ, Hornung HG, Shepherd JE, Laurence SJ. 2010. Experimental investigation of shock wave surfing. *Bul. Amer. Phys. Soc.* 55(16)

201. Sharp N, Hofferth JW, White EB. 2012. Surface roughness effects on a blunt hypersonic cone. *Bul. Amer. Phys. Soc.* 57(17)

202. Sharp NS, Hofferth J, and White EB. 2013. Discrete surface roughness effects on a blunt hypersonic cone in a quiet tunnel. *Bul. Amer. Phys. Soc.* 58(18)

203. Sivasubramanian J, Fasel H. 2009. Investigation of transition initiated by a wave packet in a hypersonic cone boundary layer. *Bul. Amer. Phys. Soc.* 54(19)

204. Sivasubramanian J, Fasel H. 2010. Investigation of a turbulent spot in a hypersonic cone boundary layer. *Bul. Amer. Phys. Soc.* 55(16)

205. Suman S, Girimaji SS, Bertsch R. 2009. Homogeneously-sheared compressible turbulence at the rapid distortion limit. *6th International Symposium on Turbulence Heat and Mass Transfer (THMT'09).* Rome, Italy

206. Suman S, Girimaji SS. 2010. Effects of Mach number and compressibility on vorticity and strain-rate turbulence dynamics. *Bul. Amer. Phys. Soc.* 55(16)

207. Suman S, Girimaji SS. 2011. Toward topology-based characterization of small-scale mixing in compressible turbulence. *Bul. Amer. Phys. Soc.* 56(18)

208. Suman S, Girimaji SS. 2012. Modeling various effects of compressibility on the pressure Hessian tensor, *Bul. Amer. Phys. Soc.* 57(17)

209. Tumin A, Lifshitz Y, Degani D. 2011. Study of discrete modes branching in high-speed boundary layers. *Bul. Amer. Phys. Soc.* 56(18)

210. Tumin A. 2009. Toward the foundation of a global modes concept. *Bul. Amer. Phys. Soc.* 54(19)

211. Ulker E, Klentzman J, Tumin A. 2011. The effect of chemistry and transport models on the inviscid stability of boundary layers in binary mixtures of oxygen and nitrogen. *Bul. Amer. Phys. Soc.* 56(18)

212. Xie Z, Girimaji SS. 2011. DNS investigation of late-stage transition in hypersonic channel flow. *Bul. Amer. Phys. Soc.* 56(18)

Oral presentations (invited lectures):

213. Bowersox R, North S. 2011. Fundamental studies of surface roughness and ablating flows. *4th Air Force, NASA, Sandia Workshop on Ablation*, Albuquerque, NM

214. Bowersox R. 2010. Modeling high-speed shear flows with non-equilibrium effects (A work in progress). Invited Lecture, *Cal Tech*

215. Bowersox R. 2011.High-speed turbulent boundary layers with roughness and global distortions (invited presentation). *49th Aerospace Sciences Meeting*, Orlando, FL

216. Bowersox R. 2012. On the modeling of high-speed turbulent flows with applications towards reentry ablation. *5th Air Force, NASA, Sandia Workshop on Ablation*, Lexington, KY

217. Bowersox RDW. 2012. High-speed boundary layers with non-equilibrium effects. Invited Lecture, *University of Illinois at Urbana-Champaign*

218. Fasel H. 2012 Direct numerical simulation of hypersonic boundary-layer transition. University of Stuttgart, Institute for Aero-and Gas Dynamics, June 24, 2012

219. Fasel H. 2012. Three-stage breakdown of hypersonic boundary layers. *International Workshop on Hypersonic Stability and Transition*, October 2-4, Sedona, AZ

220. Fasel H. 2013. Nonlinear Development in high-speed boundary-layer transition. University of Stuttgart, Institute for Aero-and Gas Dynamics, July 6, 2013

221. Fasel H. 2014. Direct numerical simulation of laminar-turbulent transition for a cone at M = 6. *Nonlinear stability theory: From weakly nonlinear theory to the verge of turbulence*, March 19-21, London, UK

222. Fedorov A, Balakumar P. 2012. Slow and fast modes in a hypersonic boundary layer. *Presented at Int. Workshop on Hypersonic Stability and Transition,* Sedona

223. Girimaji SS. 2009. Turbulence and transition research at Texas A&M University Aerospace Engineering Department. *Aerospace Engineering Department Seminar Series. Indian Institute of Technology, Bombay (Mumbai),* India

224. Girimaji SS. 2010. Compressibility effects on Turbulence. *M&AE Department, University of Florida*

225. Girimaji SS. 2013. Stability of compressible shear flows: Role and action of pressure. Invited Speaker. *EUROMECH Colloquium 542*: Progress in statistical theory and pseudo-spectral Direct Numerical Simulations, CNRS, Lyon, France

226. Girimaji, SS. 2009. Recent advances in hypersonic compressible turbulence research. *Mechanical Engineering Department Seminar Series, Stanford University*, Stanford, CA

227. Hader C, Fasel H. 2012. Numerical investigation of transition delay using porous walls for a Mach 6 boundary layer. *International Workshop on Hypersonic Stability and Transition*, October 2-4, Sedona, AZ

228. Hofferth JW, Saric WS. 2011. Recent progress in the Texas A&M Mach 6 Quiet Tunnel. *Transition Study Group Open Forum,* Honolulu, HI

229. Hofferth JW, Saric WS. 2012. The second-mode instability on a flared cone in a low-disturbance Mach 6 tunnel. *Presented at Int. Workshop on Hypersonic Stability and Transition*, Sedona

230. Hofferth JW. 2013. Boundary-layer instability and transition experiments in a Mach 6 quiet tunnel. (Invited) *California Institute of Technology*, Pasadena, CA

231. Hornung HG, Jewell JS, Parziale NJ, Shepherd JE, Valiferdowsi B. 2012. Recent research on transition at the T5 Hypervelocity Shock Tunnel. *Presented at Int. Workshop on Hypersonic Stability and Transition*, Sedona

232. Hornung HG, Karl S, Hannemann K. 2011. Sonic line and stand-off distance on reentry capsule shapes. *International Symposium on Shock Waves*, Manchester, England, UK

233. Hornung HG, Martinez-Schramm J, Hannemann, K. 2011. Bluntness effects in hypersonic flow over slender cones and wedges. *International Symposium on Shock Waves*, Manchester, England, UK

234. Hornung HG, Parziale NJ, Zhong X, Lei J. 2012. Effects of bow shock on the measurement of acoustic signal at the stagnation point in hypersonic flow over a blunt cone. *Presented at Int. Workshop on Hypersonic Stability and Transition,* Sedona

235. Hornung HG. 2009. Transition measurements in a high-enthalpy shock tunnel. *Technical University* Braunschweig, Germany

236. Hornung HG. 2010. Boundary layer transition in high-enthalpy flow. *National Cheng Kung University* Tainan, Taiwan

237. Hornung HG. 2010. Gradients at a curved shock wave. *European Fluid Mechanics Conference*, Bad Reichenhall, Germany

238. Hornung HG. 2010. Ground testing for hypersonic flow, capabilities and limitations, and selected achievements and discoveries made in high-enthalpy facilities. *von Karman Institute for Fluid Dynamics, Lecture series on Hypersonic Flow* Brussels, Belgium

239. Hornung HG. 2010. Transition between regular and Mach reflection. *National Taiwan University,* Taipei, Taiwan

240. Hornung HG. 2010. Tripping a regular shock reflection to transition to Mach reflection. *Zentrumskolloquium DLR Goettingen*

241. Hornung HG. 2011. Two effects in Mars entry aerodynamics. *Fluid Mechanics Seminar, ETH*, Zuerich, Switzerland

242. Hornung HG. 2011. Two effects of high density ratio across bow shocks. *Fluid Dynamics Award Lecture AIAA Fluid Dynamics Meeting*, Waikiki, HI

243. Hornung HG. 2012. On regular and Mach reflection of shock waves. *Fluid Mechanics Colloquium, IFD, ETH* Zuerich

244. Hornung HG. 2012. Part I: Lester Lees, hypersonics pioneer. Part II: Two effects in hypersonic boundary layer transition. *Lester Lees Lecture, GALCIT*, Pasadena, CA

245. Hornung HG. 2012. Two effects of high density ratio across shock waves. *University of Louvain-la-Neuve, Belgium*

246. Hornung. 2011. Transition between regular and Mach reflection of shock waves. *Fluid Mechanics Seminar, Melbourne University,* Australia

247. Jewel JS, Wagnild R. 2012. Transition within a hypervelocity boundary layer on a 5-degree half-angle cone in free stream air/CO2 mixtures. *Presented at Int. Workshop on Hypersonic Stability and Transition,* Sedona

248. Klentzman J, Tumin A. 2012. Receptivity of high speed boundary layers including real gas effects. *Presented at Int. Workshop on Hypersonic Stability and Transition,* Sedona

249. Klentzman J, Tumin A. 2013. Receptivity addendum to stability code report. *Technical report, University of Arizona*

250. Klentzman J, Tumin A. 2013. Stability code for high speed boundary layers in chemical non-equilibrium. *Technical report, University of Arizona*

251. Parziale NJ, Shepherd JE, Hornung HG. 2012. Geometric acoustics in a hypervelocity boundary layer. *Presented at Int. Workshop on Hypersonic Stability and Transition*, Sedona

252. Parziale NJ. Differential Interferometric Measurement of Hypervelocity Boundary Layer Instability. *Invited lecture, Texas A&M University*, College Station, TX

253. Reshotko 2010. Anatomy of a good boundary layer transition flight experiment. *NRC Study Group on NASA Flight Experimentation*

254. Reshotko E. 2009. Comments on the difference between noisy and quiet results in the Purdue BAM6QT Tunnel. *AIAA Transition Open Forum*

255. Reshotko E. 2009. Transient Growth – Theory and applications. *NASA Langley Research Center*

256. Reshotko E. 2010. Recent studies toward improved mobility efficiency in non-fighter aircraft. *Air Mobility Command*

257. Reshotko E. 2010. Transition caused by isolated roughness elements. *AIAA Transition Open Forum*

258. Reshotko E. 2011. Bill Sears – An appreciation. William R. Sears Memorial Lecture, University of Arizona

259. Reshotko E. 2012. Receptivity and growth issues for distributed roughness. *AIAA Transition Open Forum*

260. Reshotko E. 2012. Transition influences on vehicle design. *Presented at Int. Workshop on Hypersonic Stability and Transition*, Sedona

261. Reshotko E. 2012. Transition issues at hypersonic speeds. *U.S. Air Force Academy*

262. Reshotko E. 2013. Transition on entry vehicle shapes. *NATO STO ET-136*

263. Reshotko E. 2014. Roughness induced transition on entry vehicle shapes. *NATO STO WG*

264. Saric WS. 2011. Hypersonic laminar-turbulent transition studies. *VKI*, Belgium

265. Saric WS. 2011. Progress in laminar-turbulent transition – A personal career perspective. *NASA – Ames Research Center*

266. Saric WS. 2012. Progress in laminar-turbulent transition – A personal view. *Purdue University*

267. Saric WS. 2012. The second-mode instability on a flared cone in a low-disturbance Mach 6 tunnel. *TU-Braunschweig*

268. Sharp NS, Hofferth JW, White, EB. 2012. Surface roughness experiments using the TAMU transient growth cone. *Int. Workshop on Hypersonic Stability and Transition*, Sedona

269. Shepherd JE. 2012. Research on transition at the T5 Hypervelocity Shock Tunnel. *Los Alamos National Laboratory*

270. Sivasubramanian J, Fasel H. 2012. Direct numerical simulation of laminar-turbulent transition for a cone boundary layer at Mach 6. *International Workshop on Hypersonic Stability and Transition*, October 2-4, Sedona, AZ

271. Tumin A, Ulker E, Klentzman J. 2012. Boundary-layer solver for binary reacting mixtures of oxygen and nitrogen. *Technical Report, University of Arizona*

272. Tumin A. 2009. Toward foundation of a global (bi-global) modes concept. *Global Flow Instability and Control – IV,* Creta Maris, Hersonissos, Crete, Sept 28 – Oct 2, 2009

273. Tumin A. 2010. How many unstable modes are in high-speed boundary layer? *AFB Dayton*, March 2010

274. Tumin A. 2011. Stability of high-speed chemically non-equilibrium boundary layers. *KTH*, Stockholm, December 2011

275. Tumin A. 2013. Application of the bi-orthogonal eigenfunction system of linear stability equations. *Tianjin University*, Tianjin, China, August 2013

276. White EB. 2012. Transient growth in boundary layers: receptivity, realizability and realistic roughness. *Mechanical and Aerospace Engineering Department, UCLA*